A problem of optimal control and observation for distributed homogeneous multi-agent system

Cite as: AIP Conference Proceedings **1910**, 060007 (2017); https://doi.org/10.1063/1.5014001
Published Online: 07 December 2017

Sergey V. Kruglikov

A Problem of Optimal Control and Observation for Distributed Homogeneous Multi-Agent System

Sergey V. Kruglikov[1,2]

[1]*N.N. Krasovskii Institute of Mathematics and Mechanics of the Ural Branch of the Russian Academy of Sciences (IMM UB RAS) 16 S.Kovalevskaya Str., Yekaterinburg, 620990 Russia.*
[2]*Ural Federal University19 Mira pr., Yekaterinburg 620219, Russia.*

svk@imm.uran.ru

Abstract. The paper considers the implementation of a algorithm for controlling a distributed complex of several mobile multi-robots. The concept of a unified information space of the controlling system is applied. The presented information and mathematical models of participants and obstacles, as real agents, and goals and scenarios, as virtual agents, create the base forming the algorithmic and software background for computer decision support system. The controlling scheme assumes the indirect management of the robotic team on the basis of optimal control and observation problem predicting intellectual behavior in a dynamic, hostile environment. A basic content problem is a compound cargo transportation by a group of participants in the case of a distributed control scheme in the terrain with multiple obstacles.

INTRODUCTION

Most of contemporary techniques developed in mathematical theory of optimal control are based on supposition of Markov's property. Whereas a lot of problems of management in technological, economic and social systems strongly depends on possibility to forecast future behavior on the base of analogies and samples formed in advance in accordance with experiences and memories of participants. The necessity to interpret modern qualitative techniques in terms of quantitative values forms the motivation to find mathematical tools adequately excluding some of basic restrictions. Moreover, the development of advanced cognitive technologies requires to study the theoretical foundations of the combination of autonomous, centralized, distributed and decentralized (A/C/Di/De) control to get efficient algorithms of guidance, navigation and control [1-4]. Note that schemes of distributed and decentralized control reflect the difference in the concepts of distributed artificial intelligence and artificial life [5].

The paper deals within the unified understanding of management process as a procedure formed in four stages, main of which is decision-making under uncertainty and risk. The situations of uncertainty are routine ones and difference lies only in levels of admissible information (complete uncertainty, risk, conflict). Problems under consideration in the paper correspond to the case of complete uncertainty, there why techniques of guaranteed control are investigated. Stages of management process under uncertainty include:

1) Analysis of the environment and situation. Problem understanding and design of alternative solutions. Decision making tree is an adequate technique to this stage.
2) Decision making as choice of the decision, the only alternative.
3) Organizing the execution, i.e. practical implementation of the decision.
4) Monitoring the correspondence of the actual status and the objective.

So currently problems dealing with the team of UAV control are forming the core realm of interest in mathematical theory of optimal control and observation. Research is motivated by the necessity to develop the theoretical background for description and understanding of interaction of intelligent UAV[6]. The upcoming tsunami of robotization forms sharp necessity for mathematics efficient formaintaining operator-machine interaction and cooperation. Wide range of such problems statement occurs in the realm of multicomponent robotic complex (MRC) as a hierarchically organized homo- or heterogeneous set of mobile autonomous vehicles and/or remote-

Proceedings of the 43rd International Conference Applications of Mathematics in Engineering and Economics
AIP Conf. Proc. 1910, 060007-1–060007-5; https://doi.org/10.1063/1.5014001
Published by AIP Publishing. 978-0-7354-1602-4/$30.00

controlled robotic complexes (RCs), where robotic units can be groups or populations[4]. Interesting information on recent understanding of UAV operations, prospects of development and open challenges as yet unsolved problems are presented in [6]. Leaving aside strictly military range of applications urgent problems are those to develop efficient algorithms for such operations as: 3.2.3 Protection (monitoring and protection of objects and zones of special attention), 3.2.4 Logistics(transport/ search and rescue /repair operations).It is necessary to mention that Russian governmental structures turn to understanding that mobile UAVs may form the crucial tools for development of unpopulated areas in Arctic and Circumpolar zone of Russian Federation.

Main challenges forming the directions of technological rush in area of UAV include [6]: 3.6.1 Interoperability and 3.6.2 Autonomy.

Interoperability as a coordination of the work of the MRC as a whole on the basis of the interaction of actors, the MRC components, and environmental elements ought to be provided with a grid ground control station (GCS) that allows the implementation of (A/C/De/Di) control by one or several operators of individual RTCs and/or PRCs in the many-to-many communication scheme. A special case of an MRC is a multi-robot controlled by one operator.

GCS of MRC is a common ground control station, providing (possibly partial) solution of problems

- on MRC level:1) Navigation (recognition of objects and scenes, formation of environmental models, ect.)Corresponding mathematical techniques are formed by *Optimal Observation and Estimation*.

2) Guidance(planning of traffic routes and sequences of actions to achieve the goal) *Optimal Control*.

- On RC level**:** Control(traffic control taking into account the dynamics of the robot) *Optimal Stabilization*

Attempts to exclude operators leads to the problem of autonomy. It is connected with the difference between automatic and autonomous systems. An automatic system is able to follow an externally given, may be by operator, path while compensating for small deviations caused by external disturbances. The automatic system can neither to define the path according to some given goal nor to choose the goal dictating its path.

The feature of an autonomous system is its ability to be goal-directed in unpredictable situations. An autonomous system is able to make a decision based on forecast. It is able to determine what information is important in accordance with a set of rules and/or limitations. In particular, the problems of interpreting navigation, autonomous control for RTC management; guidance, coordination of the actions of the UAVs by intelligent systems of distributed control. There are different approaches to mathematical modeling of the applied questions under discussion. Some of them are presented below in Tab.1. Significant tool providing linkage of technical opportunities and Math formalization is so-called multi-agent approach. The choice of toolkit for this article is presented by underlining.

TABLE 1. Correspondence of MRC applications, multi-agent approach and guaranteed control problems

Applications	Research Areas	Math
Controlling MRC	System Analysis	Theory of Probability
• Logistics	Operation Research	Calculative Geometry
• Protection	Multi-agent approach	Optimal Control & Estimation
	IT-Simulation	under Uncertainties
	Supercomputing	Operation presentation
	AI	Algebraic approach

MULTI-AGENT APPROACH

There are possibilities to present a wide class of real objects and abstract notions in terms of (real/virtual)multi-agent systems (MAS).Various techniques mainly oriented on computer simulations have proved the efficiency in dealing with wide range of practical applications including those under uncertainty and risk. As a development of system approach multi-agent one is based on following principles.

- Communicability, possibility of data exchange between agents.
- Purposefulness, entire feature of goal orientation.
- A number of service functions.
- Autonomy, relative availability of own resources (material, energy, computing, sensory, etc.)
- Reactivity, ability to perceive an environment and to build its partial images on the basis of information received.

- Self-organization, ability to form a team capable to solve certain tasks.

Consistent development of the approach from simple cases to more and more complex cases allows to include in consideration the notions of intelligent either real or virtual agents. Nevertheless, the question of mathematical description of intelligent multi-agents is still under discussion. Further is presented one of the possible ways based on notion of unified information space of the automated control system proposing in description1) the unity of time and place,2) the unity of stimulus and reaction, 3) the parity of interacting actors.

Hierarchical formalization of interoperability

Suppose that artificial actors MRC and RTS are considered as multi-agents of different levels*[ps]S* and *[ps-k]S*, that involves the allocation of several structural levels *[km0:pm:km1]* of the hierarchical description. For MRC of the typical structure [*kx=3*] level with a compact arrangement of the group of agents; [*kx=4*] if there are separate groups within the complex. In particular, let the controllable open multi-agent system *k=0*, then *k=-1* of the subsystem be heterogeneous groups of agents, *k=-2* subsystem homogeneous PPC ..., *k = -k** components of the UAV, including the technological equipment component.

Construction of unified information space allows to depict Table.2 the isomorphic correspondence of external interaction space *[ps][**SP**(~)**SP**'(//)#**SP**'(~)#**SP**]*and internal space of images*[pm][**MP**(~)**MP**'(//)#**MP**'(~)#**MP**]j*, formed by intelligent interacting agents ***s1#s2***.

TABLE 2. Correspondence of external interaction space and internal space of images

[Ext:*ps*]**SP** ***External Invariants***	***Environment*** *[ps]**SS**Obstacles*	***Situation*** *[ps]**SS**={**S**.j}Objects*	***Event*** *[ps]**S**s(**s**0:**s**1#**s**2)Actors*
			[Ext‖Int] **NP**.*i* (r)*Agents*
[Int:*pm*] **MO**.*i* **Image *Internal Invariants***	*[pm]**MS**.i* ***Memory***(r\/v|i)*MAS*	*[pm]**MS**.i* ***Experience***(r\/v)*MAS*	*[pm]**M**s.i* ***Model of Event***(r\/v)*Agents*

Duality of ensured control-estimation problems

Similar organization of routine corresponding samples of real action, either stimulus or reaction*[ps]**s**Yj={**a**Y=(**s**1,**s**2),<AF1;AF2], **a**Y' =(**s**1,**s**2)'}j* and internal stereotype *[pm]**m**Yj={**c**Y=(**m**1,**m**2),<cF1;cF2], **c**Y' =(**m**1,**m**2)'}j* allows to support on well-known structural property of duality of the guaranteed optimal control/observation under uncertainty.

$$\min_{U} \sup_{X} \{\Phi_U(\eta)\} = \min_{U\#} \sup_{X\#} \{\Phi^*_{U\#}(\zeta^*)\}$$

Problem 1.*Management efficiency*. [Control.A|W|I].

Under assumptions given above on structure of route find an operator U^*, $U^* \in \mathbf{U}$, satisfying inequality

$$-\infty < Sup_X \{ \Phi(U\_*)\} = Min_U\, Sup_X \{\Phi(U)\} < +\infty.$$

Here $\Phi(U)=\phi(F\eta + G_0 \circ U \circ A(U)\ \eta) - \theta(h)$,values describing results $\phi(F\eta + G_0 \circ U \circ A(U)\ \eta)$ and constraints $\theta(\eta)$. $\mathbf{U}_0=\{U_0=U \circ Y_Y^{-1}(U)=Y_{Z\#}^{-1}(U) \circ U | U \in \mathbf{U}\}$;

$\mathbf{U}=\{U=U_0 \circ (E_Y+B \circ U_0)^{-1}=(E_{Z\#}+U_0 \circ B)^{-1} \circ U_0 | U_0 \in \mathbf{U}_0\}$.

Problem 2. *Risk Management*. In basic suppositions on structure of production unit find an operator V_m, such that

$$-\infty < sup\{<\phi\#(F\#\eta + G\#_0 \circ V_m \circ A\#(V_m)\ \eta) - \theta\#\{\eta)) = min\ sup\{\phi\#(F\#\eta + G\#_0 \circ V \circ A\#(V)\ \eta) - \theta\#\{\eta)\ | V \in \mathbf{U}\} < +\infty.$$

The choice of quality criteria $e = min\{\phi X\}$reflects priorities of actor as the decision making person:

- *eA* – stability of state or motion, ϕA - multiplicity *K, min{K}*
- *eW*- achieve the goals, ϕW– route length, *LL*
- *eI* - efficiency. $\phi I = (Lmax-LL)/K$

LOGISTICAL OPERATION

The implementation of controlling a homogeneous complex of several mobile multi-robots is considered. A basic content problem is a compound cargo transportation by a group of participants in the case of a distributed control scheme in the terrain with multiple obstacles. The concept of a unified information space of the controlling system is applied that makes possible the decimal digital coding of organization, position and duration; isolating typical routines [***sO(~)sN***] for software implementation and basic structural units, complex obstacles; providing flexibility of such representation of objects, borders of obstacles and passages. The information and mathematical models of participants and obstacles, as real agents, and goals and scenarios, as virtual agents, create the base forming the algorithmic and software background for computer decision support system. The controlling scheme assumes the indirect management of the robotic team based on the optimal control and observation problem predicting intellectual behavior in a dynamic, hostile environment [8].

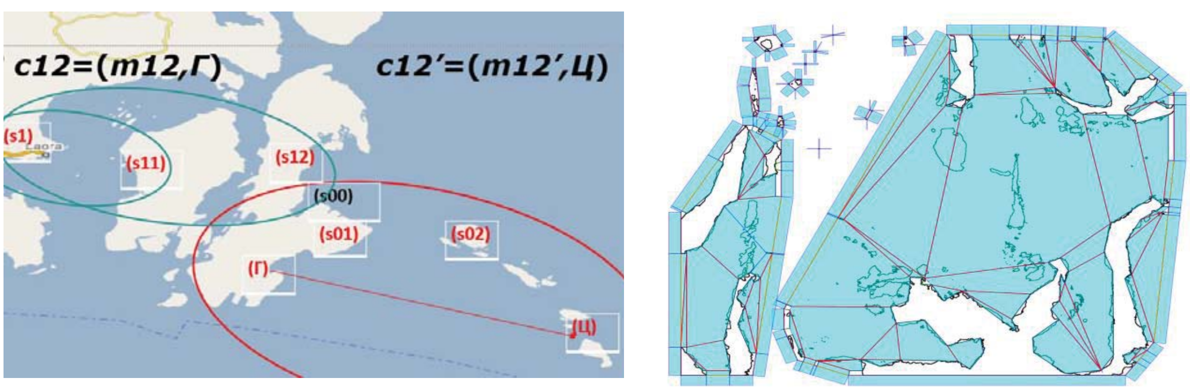
Business process of transportation *[pt]tNT* or rescue supposes movement *[ps]{**a**(#)**a'**}*, as a position changing from **a**=(**s**1,**s**2) to **a'**=(**s**1',**s**2'), in accordance with virtual model*[pm]{**c1**(#)**c1'**}, **c1***=(**m**1,**m**2)*, **c1'***=(**m**1',**m**2'). Here actor**s**1|| **m**1=*{h1,p1,t1}* is an intelligent may be multiple agent, solving the problem of cargo transporting (Г: load)**s**2 || **m**2 =*{h2,p2,t2}*, possible compound, into the target position (Ц)***s2'*** || **m**2' =*{h2',p2',t2'}*. The state of Subject may be also changed.

The unified information space of the systems gave opportunity to describe in a similar way different cases of a hierarchical complex. In particular, when actor **s**1||**m**1 has no routine to draw the load, logistic chain has to be formed. That means necessity of description for: (*h*) status in hierarchy, $h \in H \in \mathbf{H}$; (*p*) geographic location, $p \in P \in \mathbf{P}$; (*t*) duration in time $t \in T \in \mathbf{T}$. $(h,p,t) \in H \times P \times T \in \mathbf{H} \times \mathbf{P} \times \mathbf{T}$. Corresponding IT-program realization are given by such constructions:

State = struct { Level<Hierarchy>, Figure<Vector>, Interval<Time>}, Map = List<State>.

An unified information space made possible to investigate and examine several types of position description:

- Cellular map with cell-specific clarification. The description is adequate to step of separating group and forming a team capable to solve the task. In particular, logistic chain, Fig.1 a) below.
- Set of raised obstacles generated on base of regular descriptive elements (balls in 3Dcase, or circles in planar one). The description is adequate to the protection task in environment with mainly fixed restricted in amount obstacles [7].
- The graph of hierarchical system of convex passes corresponding to an arbitrary initial set of obstacles contours, Fig.1 b) below.



(a) (b)

FIGURE 1. The presentation of a logistic operation algorithm based on separation of optimal control problems under uncertainty: (a) optimal control step. Forming a team capable to transport the load (Г) to the final position (Ц), (b) optimal observation step. Forming the graph of convex passes in case of multiple obstacles.

The prototype of GCS is developed to implement logistic operations of "transport load from arbitrary initial position to final one by a UAV column through the terrain with obstacles". Presented below in Fig.1 experimental and research tests of the prototype GCS were carried out at the marine model range, which includes a terrain model.

Summary

A formalized description of the basic content operations of the homogeneous complex of mobile UAVs, which constitute the functional of the algorithms for the implementation of the prototype GCS MRC, is proposed. The developed mathematical models create a necessary base for design of algorithmic and software support for computer decision support systems, the use of mobile multi-robot complexes, unmanned technologies and intelligent information systems. In work on the basis of the methods of the mathematical theory of guaranteed control under uncertainty, an alternative to implement the concept of unified information space of the automated control system of the MRC is proposed, which allows: an unified representation of a wide range of dynamic and organizational objects of agents, compatible with the multi-agent approach; the open architecture of a team organization allowing adaptive connection of separate autonomous UAVs. A natural extension of the model is possible, depending on the changing situation and/or the application of UAVs with different maneuverability characteristics.

ACKNOWLEDGMENTS

The work was carried out with the financial support of the Basic Research Program of the Ural Branch of the Russian Academy of Sciences, Project No. 15-16-1-8.

REFERENCES

1. M.Wehrle,J.Rintanen,"Planning as satisfiability with relaxed 9-step plans," in*Advances in Artificial Intelligence*-2007, 20th Australian Joint Conference on Artificial Intelligence, pp.244-253.
2. I.A.Kaliaev, S.G.Kapustian,"Multiprocessor distributed control system of intelligent mobile robot," in Procedings 14-th Workshop on Distributed Control Systems. (Seoul, Korea, 1997).
3. A.Zapp,"Comand and control structure and perception system of the German McD experimental program "Robotics on the battlefield" in Procedings of IEEE Inter. Conf. Rob. AndAuton., (Nice, France, 1992). Vol.3, pp.2785-2791.
4. M.Buttner, J.Rintanen, "Improving parallel planning with constraints on the number of operators," in Proceedings of the 15-th International Conference on Automated Planning and Scheduling. (2005) pp. 292-299.
5. W.H. Sandholm, *Population games and evolutionary dynamics*. (MIT Press, Cambridge, Mass. 2010)
6. DoD USIR Unmanned Systems Integrated Roadmap, FY 2011-2036. (2011)
URL: https://publicintelligence.net/ dod-unmanned-systems-integrated-roadmap-fy2011-2036
7. S.V.Kruglikov,A. S.Kruglikov, Appl. Mechanics and Materials. TransTech Publications, Switzerland. **494-495**, pp. 1110-1113. (2014)
8. R. Horowitz, P. Varaiya, Proceedings of the IEEE, **88**(7), pp.913–925.